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ORIGINAL RESEARCH

Performances of Different Global Positioning System Devices for Time-Location Tracking in Air Pollution Epidemiological Studies

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Abstract

Background: People's time-location patterns are important in air pollution exposure assessment because pollution levels may vary considerably by location. A growing number of studies are using global positioning systems (GPS) to track people's time-location patterns. Many portable GPS units that archive location are commercially available at a cost that makes their use feasible for epidemiological studies.

Methods: We evaluated the performance of five portable GPS data loggers and two GPS cell phones by examining positional accuracy in typical locations (indoor, outdoor, in-vehicle) and factors that influence satellite reception (building material, building type), acquisition time (cold and warm start), battery life, and adequacy of memory for data storage. We examined stationary locations (eg, indoor, outdoor) and mobile environments (eg, walking, traveling by vehicle or bus) and compared GPS locations to highly-resolved US Geological Survey (USGS) and Digital Orthophoto Quarter Quadrangle (DOQQ) maps.

Results: The battery life of our tested instruments ranged from <9 hours to 48 hours. The acquisition of location time after startup ranged from a few seconds to >20 minutes and varied significantly by building structure type and by cold or warm start. No GPS device was found to have consistently superior performance with regard to spatial accuracy and signal loss. At fixed outdoor locations, 65%–95% of GPS points fell within 20-m of the corresponding DOQQ locations for all the devices. At fixed indoor locations, 50%–80% of GPS points fell within 20-m of the corresponding DOQQ locations for all the devices except one. Most of the GPS devices performed well during commuting on a freeway, with >80% of points within 10-m of the DOQQ route, but the performance was significantly impacted by surrounding structures on surface streets in highly urbanized areas.

Conclusions: All the tested GPS devices had limitations, but we identified several devices which showed promising performance for tracking subjects' time location patterns in epidemiological studies.

Keywords: global positioning systems, GPS, time activity

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Background

The knowledge of where individuals spend their time is an essential component of human exposure assessment and environmental epidemiology. Such time-location information can be linked with corresponding pollutant concentration data to improve estimates of personal exposures.[1] Conventional time-location data are collected by recall interviews or diaries,[2,3] but these are limited by accuracy of recall, reliability, reproducibility, and compliance.[4] Recently, new techniques have been used to improve the traditional methods that collect time-location data, including video-taping children's micro-activities (eg, hand-to-mouth behaviors) for a short period of time and tracking people's time-location patterns or commuting behaviors using portable global positioning system (GPS) technology with or without corresponding traditional diary information.[4–11] The GPS determines geographic location (ie, latitude, longitude and altitude) and time with four or more earth-orbiting satellites. The use of GPS for human tracking presents an enormous opportunity for improving our understanding of the space-time activities of individuals and how they influence environmental exposure and health outcomes.[12]

Three factors determine the spatial accuracy of the GPS data: the availability and spatial distribution of satellites, the surrounding environment, and the GPS chip and antenna which varies across individual manufacturers. Certain GPS devices output diagnostic information for recorded locations such as the number of available satellites and dilution of precision (DOP) which measure satellite signal quality and positional accuracy. Horizontal DOP (HDOP) indicates the quality of a horizontal position (latitude and longitude) based on satellite geometry; low HDOP value indicates widely-dispersed satellites and potentially higher positional accuracy. Differential-corrected GPS have been incorporated in certain GPS devices to improve spatial accuracy and minimize bias by calibrating a given location by the measured location of a base station relative to its true location.[6] GPS proximity to high steel-frame structures in urban areas may impact positional accuracy given they may reflect satellite signals and cause them to bounce many times before reaching a GPS device. This multipath problem leads to errors in the distance calculation in GPS.[13]

Recent technological advances and consumer demand for location-aware technologies have made commercially available GPS receivers smaller, more accurate, energy efficient, user friendly, and more accessible to researchers.[6,8] However, challenges exist in adequately classifying individuals' time location patterns in air pollution epidemiological studies. Air pollutant concentrations can vary significantly by space and time.[1] For instance, traffic-generated air pollutants such as ultrafine particles and volatile organic compounds can be up to ten times higher inside a vehicle than ambient outdoors.[14–17] Pollutant levels can be much higher indoors than outdoors for those with predominant indoor sources (eg, radon and secondhand smoke) and vice versa for those mainly generated outdoors (eg, ozone).[18,19] In addition, usually concentrations of ozone peak during afternoon while primary emissions from traffic exhaust peak during early morning and evening. The time a human subject spends in major microenvironments (eg, indoor, outdoor, and in-transit) can be either used as surrogates of exposure (eg, outdoor time for ozone exposure) or combined with measured or modeled microenvironmental-level pollutant concentration data to estimate total personal exposures.[20] To reduce exposure errors, it is important to reliably classify time-stamped locations because they are directly linked to personal exposure levels. In addition to the challenge of spatial accuracy, air pollution studies that focus on mid- to long-term health effects (eg, pregnancy outcome, lung function, and cancer) require long-term exposure and activity tracking, thus it is important that the use of GPS devices minimize the need for subject intervention (eg, charging the device or downloading the data) to help achieve higher compliance rates.

Objectives

There have only been limited analyses[21,22] on how key parameters vary across various GPS devices. The main objective of this paper is to examine the capabilities and accuracy of several commercially-available portable GPS devices to assess their feasibility for human time-activity tracking in air pollution epidemiological studies. When compared to the previous studies, we focus more on challenging locations (eg, indoor, outdoor adjacent to the building structures, in-transit, and street canyon conditions) that often raise problems in studies that need continuous time activity profiles. In addition, we focus more on documenting the range of important parameters rather than sophisticated statistical analysis. Results have implications for the section of devices and the analysis of GPS data in future air pollution epidemiological studies as well as a variety of other health-related studies that use GPS technology to track subjects' physical and time-location patterns.[12,21,23–26]

Methods

We tested five commercially-available portable GPS data loggers and two GPS-enabled cell phones (Table 1) with regards to five parameters with potential importance to epidemiological studies: battery life, adequacy of memory for extended data storage, GPS signal acquisition time, GPS signal loss, and positional accuracy in different types of buildings and microenvironments. Reliable power is essential for collecting consistent time-activity data over extended periods of time. Memory is also important for extended field sampling and long-term time-activity patterns (eg, one week to one month) because insufficient memory will cause data loss. Acquisition time reflects the ability of a GPS device to quickly fix locations at start-up or after periods of signal loss. It is important to adequately capture when a person starts the GPS device or leaves a building; misclassification of microenvironments or missing activity data may occur in cases of extremely long acquisition effects. The last two parameters we tested, GPS signal loss and spatial accuracy, directly reflect the quality and completeness of the GPS data. Missing and inaccurate GPS data increase complexity in post-data processing and directly lead to location and exposure misclassification for human subjects. The flowchart of our testing procedures is listed in Figure 1 and more details are described below.

All the experiments were conducted in two areas in southern California, Irvine and downtown Los Angeles, and run at least twice on separate days between November 19, 2009 and January 6, 2010. In each test, all the GPS devices were carried in a small nylon bag, turned on within a minute of each other, and run concurrently on battery power. The devices were placed on a table or desk near the window while indoors, on the ground while outdoors, and on the adjacent passenger seat while in a vehicle or a bus. All devices except the GPhone were programmed to archive data at the same recording interval of 5 seconds and were checked before each test to optimize performance according to their manuals. At the time the experiments were conducted, the software for the GPhone (My Tracks program from http://mytracks.appspot.com/) did not have an option to set a recording interval by time; rather, it recorded based on a distance criterion, ie, the device recorded a point only if the distance between the new and the last recorded point was greater than 20 meters.

Device selection

The GPS devices (Table 1) were selected based on their potential for tracking people's time-location patterns in air pollution epidemiological studies. We have used the DG-100 from GlobalSat in a previous study[27] and WBT-201 from Wintec has been used in the Fresno Asthmatic Children's Environment Study in California.[28] The other units were selected because of their small size, convenience of use, and advertised battery life and spatial accuracy. In the pilot stage of this study, we conducted preliminary evaluations of Super Trackstick from Trackstick (~US$198) and the high-end GeoExplorer 2008 from Trimble (~US$5000), but they were not included in the final assessment because both were largely inadequate for extended subject tracking in air pollution epidemiology studies. The Super Trackstick had poor capability to capture satellite signals indoors (data not shown) compared to the GPS data devices evaluated, and the Trimble unit was expensive, heavy and bulky, had difficult-to-use software, and provided no data when experiencing poor satellite signals (eg, indoors) although it had the highest spatial accuracy among all the data loggers outdoors.

Battery life evaluation

We first fully charged all the devices, turned them on at the same time, and left them running statically for three days on a desk near the window of a 3-story wood-structure apartment (2nd floor). The battery life was estimated by subtracting the time of the last record by the time each device was turned on.

Memory for data storage evaluation

The maximum number of records on each device was either directly obtained from the manual or calculated

Table 1. Portable GPS data loggers tested in this study.

	Company	Chip/channels	Motion detection	Memory (points/days at 5 second interval)	Claimed/(tested battery life 1, 2)[a] (hours)	Claimed accuracy	WAAS[b] support	Weight (gram)	Bluetooth	Price[c] (US$)
GPS data loggers										
WBT-201	Wintec	u-Nav + iTrax, 16 channels	No	131,072/7.6	15/(19, 18)	3 m	Yes	48	Yes	94
DG-100	GlobalSat	SiRF starIII, 20 channels	No	60,000/3.5	20/(17, NA)	5 m	Yes	227	No	70
BT-335	GlobalSat	SiRF starIII, 20 channels	No	60,000/3.5	25/(22, 24)	5 m	Yes	75	Yes	63
VGPS-900	Visiontac	MTK II, 51 channels	No	SD card[d]	24/(18, NA)	1.5 m	Yes	55	Yes	95
BT-Q1000x	Qstarz	MTK, 51 channel	Yes	200,000/11.6	42/(48, 45)	2.5 m	Yes	65	Yes	95
GPS receiver or embedded GPS module with cell phones										
GPhone	HTC (android system)	Not known	Yes	SD card[d]	NA/(9, NA)	NA	No	128	Yes	99[e]
E71 cell phone	Nokia[f]	Not known	No	SD card[d]	NA/(21, NA)	NA	No	126	Yes	345

Notes: [a]Tested battery life 1 and 2 were obtained with the device outputting at 5- and 60-second interval, respectively; NA for battery life means no claimed battery life or tests were conducted; [b]WAAS: Wide Area Augmentation System which can provide higher spatial precision based on GPS satellites and ground based stations; [c]Price: All the prices based on www.amazon.com on July 22, 2010 except GPhone; [d]Points/days vary based on SD card size; [e]This is the price with Sprint month service fee of $69.99; [f]Logger software from CENS at the University of California, Los Angeles. E71 was not registered in the cell phone network.

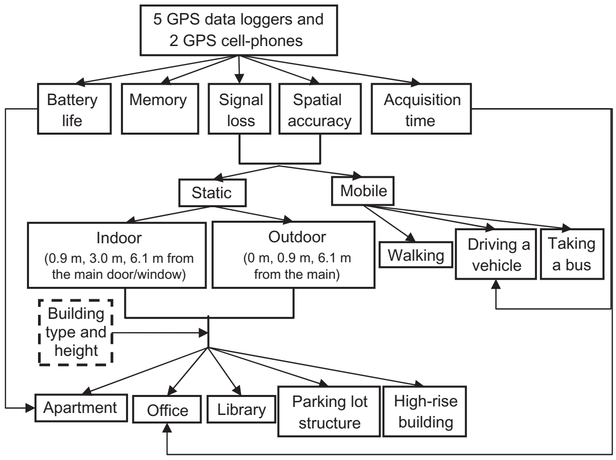

Figure 1. Flowchart of the experiments.

based on the capacity of the memory card and the size of a GPS record.

GPS signal acquisition time evaluation

Acquisition time for cold start and warm start was tested separately for each device under three conditions near the University of California, Irvine (UCI): at a single location (static) indoors in a 2-story UCI wood frame office building, static outdoors in the open parking lot outside the UCI office, and driving in a car on the UCI campus. Cold start means that the GPS devices were turned on at least one day after the last time use with location fixed, while warm start means the devices were turned on within 4 hours since the last time use with location fixed. In the acquisition time test, we turned on the devices then waited for an indication that the device had determined a location (eg, blinking green light). Acquisition time was derived by subtracting the time when the unit output the first valid record from the time when the unit was turned on. For the evaluation during driving, the GPS devices were turned on right before the vehicle started moving.

Signal loss and spatial accuracy evaluation

We examined three microenvironments where people spend most of their time (indoor, outdoor, and in-vehicle) by the type of building structure for static tests (eg, wood frame vs. concrete/steel, and by building heights) and the type of vehicle for in-vehicle mobile tests (eg, passenger car and bus). Static or fixed location tests and mobile tests were conducted to examine GPS signal loss rates and spatial accuracy for different devices. The static tests aimed to determine how well indoor and outdoor location could be identified in different environments. The mobile tests aimed to examine the GPS performance under three moving conditions: walking, driving, and taking a bus. Signal loss rate was calculated by dividing the missing number of records by the expected number of records at a given recording interval during each testing period. Statistics on spatial accuracy were conducted by comparing the geographic position of GPS location points to the US Geological Survey (USGS) 1 Meter Digital Orthophoto Quarter Quadrangle (DOQQ) images, which served as the "gold standard" for our evaluation of the spatial accuracy.

For the static tests we selected four sites on the UCI campus [the 5-story concrete Langson Library (1st floor), a 2-story wooden-structure office (1st floor), a 6-story concrete parking lot (1st floor), and a 3-story wooden-structure apartment (2nd floor)] and one site located on the campus of the University of Southern California (USC) in Los Angeles [the 11-story concrete Seeley G. Mudd Building (1st floor)]. For each of the following six predefined sites we conducted 17 minutes of measurements: three outdoor locations at 0.9, 3.0, and 6.1 m (3, 10 and 20 feet) away from the window (apartment only) or main door, and three indoor locations at 0, 0.9, and 6.1 m (0, 3 and 10 feet) away from the window (apartment only), and main door, respectively. In the spatial accuracy analysis, we removed the first minute of GPS data because unstable records may occur immediately after turning on or relocating the instruments from one location to another. In addition to summary statistics of spatial errors, we estimated the percentage of GPS points falling inside 5-m, 10-m, and 20-m buffers around the DOQQ sampling location under different conditions. The distance thresholds were selected based on previous research,[29] manufacturer-claimed accuracy of tested instruments (2–5 m), and the width of building structures and roadways near the monitoring location.

To examine error patterns across different natural and built environments during the mobile tests, we designed six routes based on site visits and Google Earth maps showing 3-D building structures. The six routes included a 30-minute walk, a 30-minute drive, and a 20-minute bus commute in downtown Los Angeles, a 40-minute drive on the I-5 freeway, and a 30-minute walk and a 20-minute bus commute near the UCI campus. The routes in Los Angeles passed skyscrapers and medium-rise buildings, and the routes near the UCI campus passed low-to-medium rise buildings and tall trees on both sides of the roads. To make the routes easily identifiable on the USGS DOQQ maps, we walked on the left side of the sidewalk and recorded the lane taken while driving. For the UCI walking tests, we followed prominent features on the roads which can be visually identified on the DOQQ map.

Results

All the GPS devices had a tested battery life of more than 15 hours except the GPhone (Table 1). BT-Q1000x had the longest battery life of 45 hours, while the GPhone had the shortest battery life (≤9 hours). No remarkable differences were observed in battery life when the recording interval was changed from every 5 seconds to every 60 seconds. The GPS cell phones could have a shorter battery life if they were used for calling and other purposes while recording GPS data.

All the tested GPS device manufacturers claimed memory capacity which could store at least 16 hours of data at a 5-second recording interval (Table 1). VGPS900, GPhone and E71 had a slot for a standard memory card, and the size of the memory card used determines how many hours of data could be stored. A 1 Gigabyte memory card can store almost 4 million GPS location records, corresponding to 230 days records at a 5-second recording interval. Although this functionality was not tested in this study, the GPhone and E71 have the capacity to upload data automatically, which further reduces the need for high-capacity memory cards. This function, however, could significantly reduce the battery life of the GPS cell phones.

Table 2 shows the GPS signal acquisition time after startup under cold and warm start conditions, respectively. Overall, GPhone and BT-Q1000x were the fastest devices to fix location across indoor (the 2-story wood office) and outdoor (parking lot around office) static microenvironments. As expected, the instruments had shorter acquisition time in warm starts than in cold starts under most conditions. In cold starts, all GPS devices except E71 received satellite signals within 70 seconds at a static outdoor location in the parking lot, 6 minutes while moving in a vehicle, and 15 minutes at a static location inside the office. During warm starts, all GPS devices except E71 received satellite signals within 30 seconds at the static outdoor location, 10 seconds while driving outdoors, and 180 seconds at the static indoor location in the office. E71 was unable to fix location after 20 minutes indoors in the office building regardless of cold or warm start.

Table 3 summarizes the spatial errors, defined as the distance to corresponding DOQQ locations. Since our main purpose is to automate subjects' time-activity patterns in air pollution-related health studies, we are concerned more about relatively small spatial errors that can cause location misclassification than large errors that can be easily detected and removed from the dataset based on the continuation of the GPS data in time and space. To reduce the impact of extreme outliers (eg, up to 30 km for the GPhone and 16 km for WBT-201) on statistics, we excluded records more than 1000 m away from the corresponding DOQQ locations. Exotic outputs from the GPhone usually occurred after the GPS program ran for a relatively

Table 2. Average GPS signal acquisition time from two tests for cold and warm starts (unit: seconds).

Experiment		WBT-201		DG-100		BT-335		VGPS-900		BT-Q1000x		GPhone		E71	
		1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd	1st	2nd
Indoor office	Cold	600	420	420	180	420	900	360	60	60	20	120	60	NA[a]	NA[a]
static)	Warm	120	180	30	30	90	90	90	90	30	30	20	20	NA[a]	NA[a]
Outdoor office	Cold	60	35	60	50	60	70	60	40	20	15	20	30	120	210
(static)	Warm	60	<5	30	<5	30	15	10	<5	30	10	20	<5	90	180
Outdoor (moving)	Cold	190	180	100	40	180	140	65	50	125	360	280	110	700	780
	Warm	<5	<5	<5	<5	<5	<5	<5	10	<5	<5	<5	<5	240	71

Note: [a]No data after 20 minutes.

Table 3. Summary statistics of the spatial errors (unit: meters).[a]

Type	HDOP (mean ± SD[b])	Statistics	WBT-201	DG-100	BT-335	VGPS-900	BT-Q1000x	GPhone[c]	E71
Static Indoor 3.0 m from a window or a door	1.7 ± 2.6	Standard deviation	52.1	14.1	25.7	34.4	25.2	6.4	12.8
		Minimum	2.3	0.4	0.7	0.7	0.2	1.8	1.3
		1st quartile	10.7	6.2	6.7	6.5	10.0	5.0	8.8
		Median	20.8	10.2	9.9	10.0	12.2	7.3	14.6
		3rd quartile	40.6	15.2	15.2	19.9	21.6	8.8	23.0
		Maximum	656.8	304.4	385.0	156.7	328.8	43.0	120.3
		Percentage within 1000 m	100%	100%	100%	100%	100%	100%	100%
		Total number of records	1195	1309	1223	1332	1929	105	792
Static Outdoor 6.1 m from a window or a door	1.5 ± 1.5	Standard deviation	47.1	7.3	10.9	9.9	5.1	9.7	25.8
		Minimum	0.6	0.1	0	0	1.3	1	0.6
		1st quartile	2.2	2.6	2.4	3.7	8.2	9.2	8
		Median	8.6	4.5	4.1	8.7	10.2	16.3	12
		3rd quartile	21.5	9.1	7.4	12	12.6	23.6	18.1
		Maximum	969.7	77.3	138	78.7	46.4	69.1	742
		Percentage within 1000 m	94.8%	100%	100%	100%	100%	70.1%	99.9%
		Total number of records	1946	2130	2062	2109	2167	314	1192
Mobile	1.0 ± 0.4	Standard deviation	21.9	10.0	13.7	13.1	9.0	9.2	27.8
		Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0
		1st quartile	2.2	1.7	1.5	2.3	2.0	1.9	2.3
		Median	4.9	3.5	3.5	5.0	4.6	4.2	5.5
		3rd quartile	12.2	6.8	7.0	10.0	9.1	8.4	11.1
		Maximum	287.0	125.0	183.9	163.7	87.2	133.0	534.6
		Percentage within 1000 m	95.8%	100%	100%	100%	100%	100%	100%
		Total number of records	4209	4693	4530	4737	4789	16002	2796

Notes: [a]Excluding records with spatial errors >1000 meters; [b]0.3% of indoor records with HDOP equals 99.99 were excluded because it indicated no fix of the GPS device. SD: standard deviation. HDOP was obtained from the BT-Q1000x device; [c]The Gphone output much less records under static conditions and much more records under moving conditions than the other instruments because its recording interval was based on distance (ie, >20 m) while the others were based on 5 second interval.

long time, and rebooting the device solved the problem. BT-335 and DG-100 had somewhat lower median spatial errors than the other devices. As expected, the spatial errors were generally larger in indoor environments than in outdoor and the mobile environments. Median errors were particularly low across all units in the mobile tests including in-vehicle traveling. The average HDOP value (recorded by BT-Q1000x) was the lowest for the mobile tests, followed by the static outdoor tests and then static indoor tests (Table 3), which partly explains the higher spatial accuracy in the mobile tests because lower HDOP generally indicates more satellites or a wider spread of satellites, factors linked to higher spatial accuracy. However, the standard deviation and the maximum value of spatial errors were larger in the mobile tests than the static outdoor tests for most of the tested devices. Further investigation showed that the high spatial errors in the mobile tests occurred mostly in downtown Los Angeles and usually lasted for 1–2 minutes, which may have been caused by satellite signal blockage when the vehicle passed by high buildings.

Figure 2 shows the average percentages of GPS records falling within the 5-m, 10-m, and 20-m buffer of the DOQQ reference locations in the 17-minutes static spatial accuracy tests for indoor and outdoor

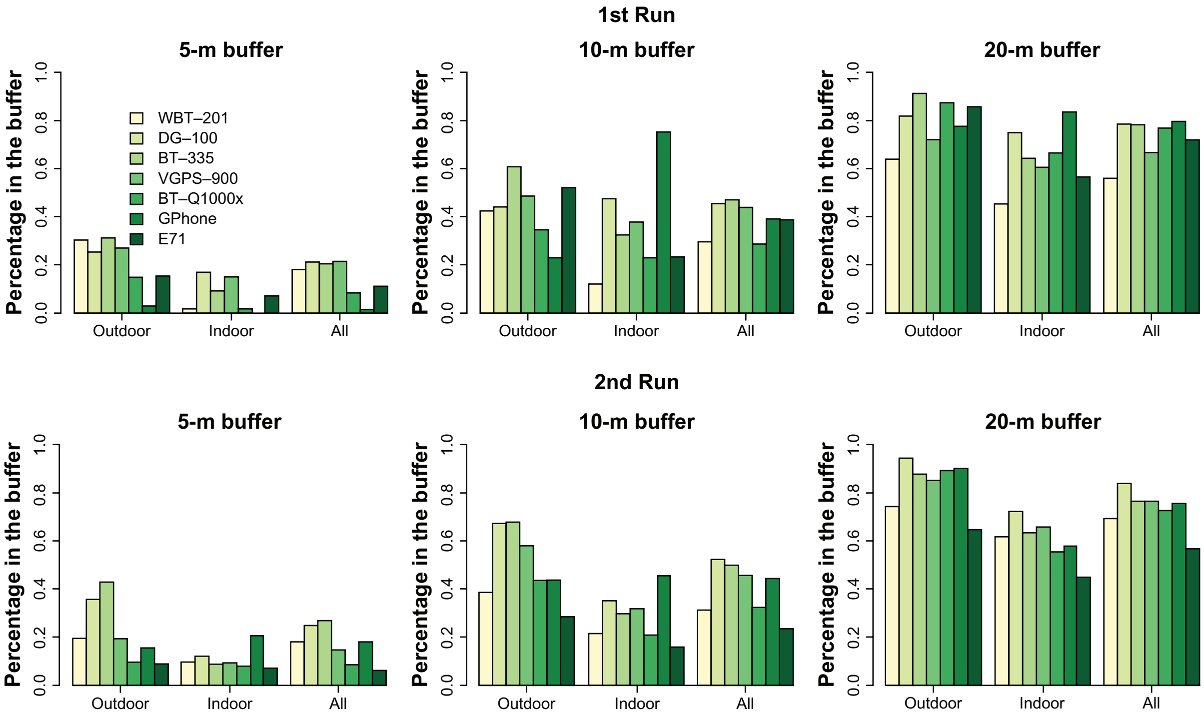

Figure 2. Percentage of recorded GPS data points in 5-m, 10-m, and 20-m buffers of indoor, outdoor, and combined indoor/outdoor samples 3.0 m from the major door or window based on the 17-minutes[a] static tests.
Note: [a]The first minute of GPS data was removed because unstable records may occur immediately after turning on or relocating the instruments from one location to another.

locations. We present results for duplicate tests (called runs) separately. As expected, the percentage of GPS points in each buffer increased with the buffer size. GPhone and BT-Q1000x had <20% of the points within the 5-m buffer but approximately 80% of the points within the 20-m buffer. Spatial accuracy was greater outdoors than indoors for many devices, but this result was not uniform. In the outdoor environments, BT-335 performed the best, followed closely by DG-100. In the indoor environments, DG-100 and GPhone outperformed the other devices, with the GPhone outperforming all the other instruments at 10-m accuracy. Among GPS loggers, if indoor and outdoor locations were combined, BT-335 and DG-100 performed slightly better than the other devices.

Based on a subset of data in Figure 2 (indoor or outdoor samples 3.0 m from the major door or window), Figure 3 shows the percentage of GPS data falling within 20-m of DOQQ reference sites by microenvironment. No GPS device was found to have consistently superior performance. All devices performed better outdoors than indoors under most conditions except for the GPhone in the UCI 2-story wood office and the USC 11-story concrete high-rise building. The devices had the worst performance indoors in the UCI library, likely because of the completely blocked sky at the sampling point by the surrounding high buildings. In comparison, better GPS performance was observed inside the concrete parking structure because it had open walls through which the devices could view part of the sky.

These results could vary depending on the distance threshold used. We use 20-m accuracy data in Figure 3 because the results across microenvironments and devices between the runs were relatively stable at 20-m accuracy, comparable analysis at the 10-m accuracy threshold contained considerable fluctuation, particularly for VGPS-900 and BT-Q1000x at apartment outdoors (Additional Files Fig. S1). This fluctuation cannot be explained by differences in the HDOP values (on average the HDOP value was 1.2 in the 1st run and 1.0 in the 2nd run), and may likely be caused by multiple-path errors when the sampling sites are close to buildings (3.0 m in this case).

Figure 4 shows the percentage of GPS data falling within 10-m and 20-m buffers of the corresponding DOQQ routes under mobile conditions. We did not show 5-m buffer results because usually a road was more than 10 m wide and the reported accuracy

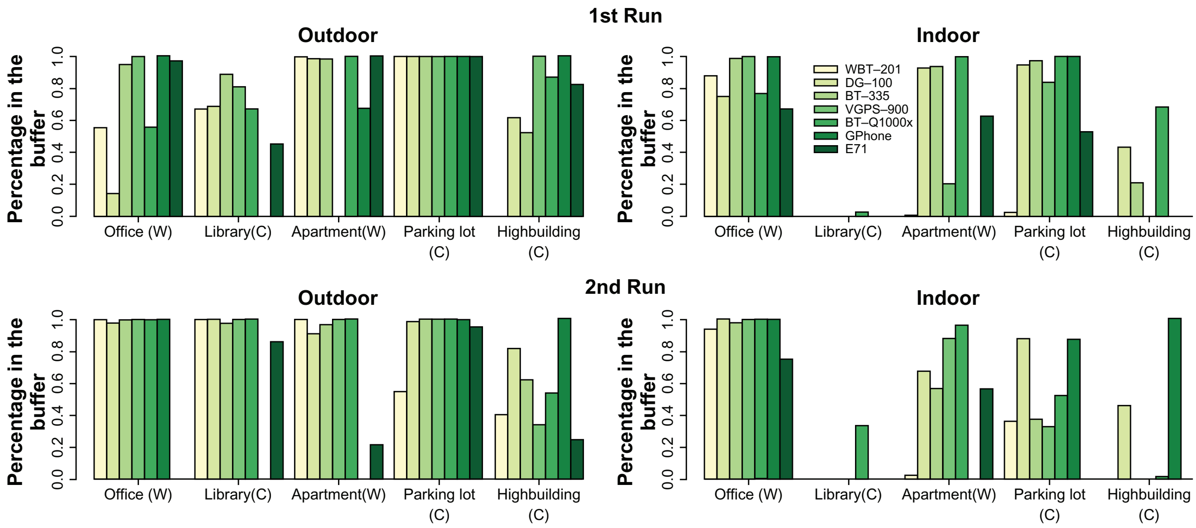

Figure 3. Percentage of recorded GPS data points in a 20-m buffer of individual sampling sites 3.0 m from the major door or window in the 17-minutes[a] static place tests (W: wood, C: concrete).
Note: [a]The first minute of GPS data was removed because unstable records may occur immediately after turning on or relocating the instruments from one location to another.

of the GPS devices ranged from 2–5 m according to the product specifications. All the devices performed well while in a passenger vehicle on the I-5 and I-405 freeways, with >75% (the 1st run) and >88% (the 2nd run) of points within 10-m of the corresponding DOQQ route except WBT-201 in the 1st run. GPS performance during walking did not differ much between the UCI route and the LA route in the 1st run but higher accuracy was observed on the UCI route in the 2nd run. Despite dense high buildings surrounding the LA bus route, the performance of the GPS devices was only slightly better on the UCI bus route than on the LA bus route. In downtown LA, somewhat better GPS performance was observed for traveling by bus and car than by walking, possibly because the driving or bus routes were further away from adjacent high buildings than sidewalk walking routes.

Figure 5 quantifies signal loss rates for all the devices which could record data at a regular temporal interval. We excluded the GPhone because it did not

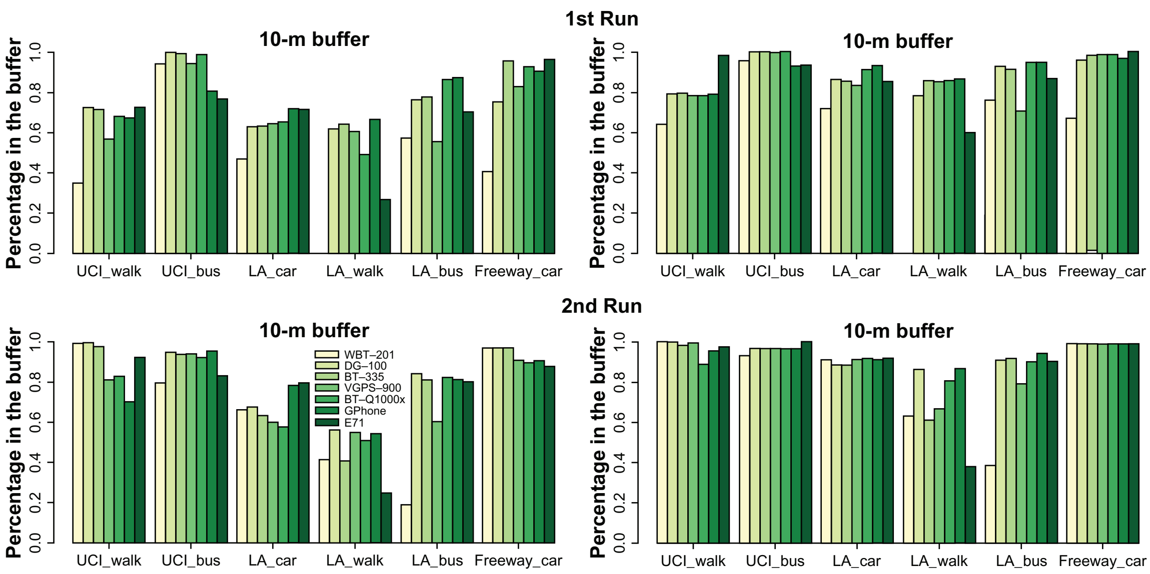

Figure 4. Percentage of recorded GPS data points in 10-m and 20-m buffers for different 30–60 minutes mobile tests.

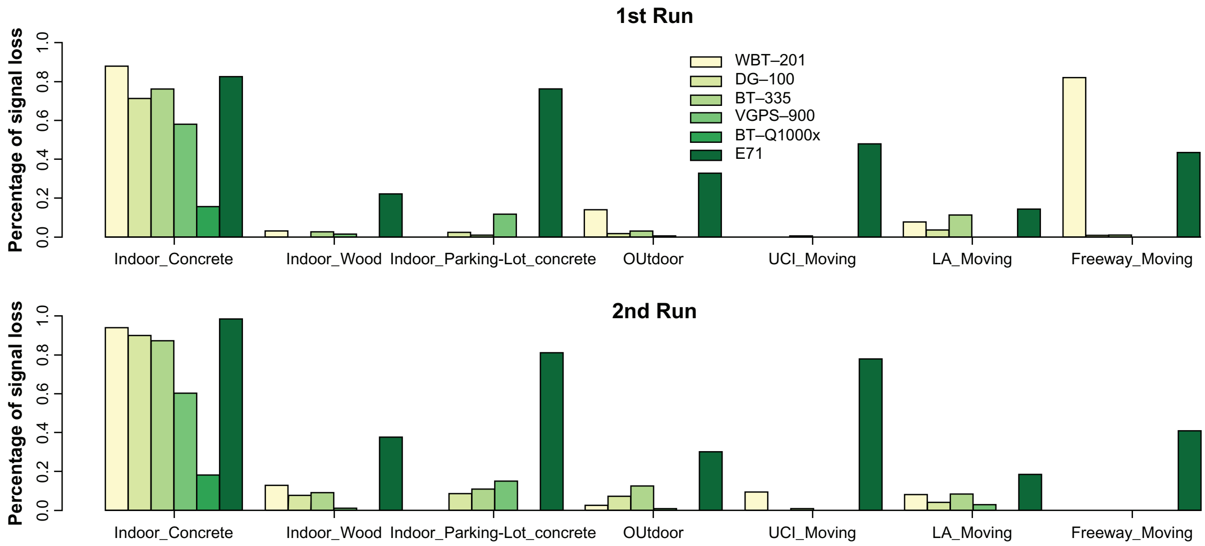

Figure 5. Signal loss rates.

record location data on regular temporal intervals but only when a new location was greater than 20-m from the previous location. We combined report results for indoor monitoring at two concrete buildings (the USC high-rise building and the UCI library) and two wood structures (the UCI apartment and the UCI office). GPS signal loss was more severe in the indoor concrete environment than the indoor wood and parking lot environments because solid concrete walls can block more satellite signals than wood walls or open concrete walls. Under the condition of relatively poor GPS signals (eg, indoors), BT-Q1000x had the lowest percentage of signal loss. Most devices except E71 (which performed worst in all situations) and WBT-201 had a small rate of signal loss (<15%) in the mobile environments, with almost zero signal loss when driving on freeways and driving/walking on the UCI campus.

Discussion

To our knowledge, this is one of the first studies that systematically examined the performance of different GPS data loggers and GPS cell phones in microenvironments which people frequent during common daily activities, particular "difficult" locations such as indoor, outdoor adjacent to building structures, in-transit, and street canyon conditions. We found that no single GPS device constantly outperformed the others, but the BT-Q1000x, BT-335, DG-100, and VGPS-900 data loggers are good candidates for daily monitoring of people's time-location patterns in air pollution health studies (Table 4). The GPhone would also be an excellent choice if the battery life, the reliability of recording programs, and the ability to support customized applications improve in the near future. BT-Q1000x had the longest battery life (almost two days), short acquisition time, and

Table 4. Summary of the tested features of all the GPS devices.

Rank	Battery life	Memory	Acquisition time	Signal loss	Spatial accuracy	Additional features
WBT-201	Fair	Fair	Fair	Fair	Bad	N/A
DG-100[a]	Fair	Bad	Fair	Fair	Good	N/A
BT-335[a]	Fair	Bad	Fair	Fair	Good	N/A
VGPS-900[a]	Fair	Good	Fair	Fair	Fair	Voice recording
BT-Q1000x[a]	Good	Fair	Good	Good	Fair	N/A
GPhone	Bad	Good	Good	N/A[b]	Fair	Automatic data upload
E71 cell phone	Fair	Good	Bad	Bad	Bad	Automatic data upload

Notes: [a]Good candidates of GPS data loggers for monitoring human time location patterns daily or weekly; [b]No signal loss rate was calculated for the GPhone because at the time the experiments were conducted, the software for the GPhone (My tracks program from http://mytracks.appspot.com/) did not have an option to set a recording interval by time; rather, it recorded location only after the device was greater than 20-m from the previous location.

low signal loss rate, making it suitable for tracking weekly or longer-term time-location information of human subjects. DG-100 and BT-335 were relatively stable regarding spatial accuracy, but they had a somewhat short battery life (17–24 hours). VGPS-900 was strong in memory capacity and other parameters, and had the capability of voice recording which makes it helpful in documenting information other than time and location (eg, physical activities such as cooking or smoking). Although we focused on the GPS applications in air pollution epidemiological studies, our results may also provide helpful information to other research fields, including transportation research,[11] human physical activity measurement,[21,24,25] and other health studies (eg, infectious disease).[12,26]

Two major limitations exist in this study. First, due to resource limitations we tested only one unit in each selected model; the single unit we selected may not be representative of other units in the same model. However, we did examine the representativeness of the single unit for the devices with two or more units (ie, DG-100, WBT-201, and BT-Q1000x) and found no significant device-to-device variations for the same model (data not shown). The other limitation is that we repeated most of the tests only twice in this study. Notable run-to-run variations were observed between the two runs (Figs. 2–5). However, despite the uncertainties, we think our results of the range of accuracy issues/concerns and the focus of the challenging environments contribute insightful understanding to the quality and performance of different GPS devices in real-world GPS tracking of human subjects.

Literature Review

Stopher et al[11] summarized the history, development, and application of three generations of GPS devices (from earlier models in 1990s to more competent models presently) for travel behavior and human time activity research. Despite the focus of the GPS devices developed by the authors' institution, the paper clearly demonstrates the rapid development trend in GPS technologies and the complexity of influential factors in GPS applications. However, there have only been limited studies on how key parameters vary across various GPS devices[6,9,11,21,22,29,30] and most of these studies focused on only one single GPS device.

Phillips et al[9] tested a March II-E GPS data recorder (Corvallis Microtechnology, Corvallis, OR). This study reported 10–20 m in spatial error and highlighted the battery life problem in the tested GPS units. Elgethun et al[6] examined the performance of a customized GPS data logger for children's time-location tracking. They reported an average spatial error of 2.5 m outdoors and 4.8 m indoors (single-story wood-frame building) at static locations. The signal loss rate was approximately 100% and 50% inside the concrete/steel frame building and the wood-frame building, respectively. In addition, power substation, microwave oven operation, and the use of cordless phone were identified as major sources of GPS signal interference. Rodriquez et al[25] reported the validity and inter-unit reliability of six Foretrex 201 GPS units (Garmin Ltd., Olathe, KS). The units had a battery life of approximately 16 hours and operated for 59% of the time for 3 day tracking of 32 adults. At an outdoor geodetic location, the average spatial error and inter-unit variation was 3 m and 0.9 m, respectively. Vazquez-Prokopec et al[26] examined the feasibility of six GPS data loggers for tracking human movements in relationship to dengue virus transmission in Iquitos, Peru, an area with low-rise buildings and wide streets. The Igot-U GT100 from Mobile Action was selected for thorough evaluation in field experiments. The battery life of the GT100 increased from 4.5 hours to 2–3 days when the sampling interval was decreased from 1 second to 2–3 minutes. The study reported 75% and 49% of the GPS points within 5 m of the actual static locations and moving routes, respectively. Rainham et al[8] thoroughly tested a customized GPS data logger (HeraLogger) with long battery life (up to 70 hours). The study reported the spatial accuracy being 7 m in typical urban environments, much inferior in urban canyon conditions, and influenced by both built environment and travel mode under moving conditions. Adams et al[30] examined the performance of a GPS receiver (GPSMap 60Cx, Garmin Inc., Olathe, KS) in different built environments. The study reported that the 98th percentile of spatial errors averaged approximately 4 m at outdoor locations, 7 m in the living room of a wood-framed, single-story home, and 33 m in the office (with exterior windows) in a concrete masonry building. Signal loss was insignificant outdoors, in the residential structure, and in the offices with exterior windows, but was more than 99% in the windowless room in the concrete masonry building.

In addition to GPS data loggers, a few studies have examined the use of GPS-enabled cell phones in tracking time locations.[21,22,29,31] Wiehe et al[21] used Blackberry 7520 GPS-enabled cell phones to track the travel patterns of adolescents. The study showed that user error (eg, subject incompliance) and technical issues relating to the GPS functionality were two major issues influencing the reliability of the GPS data collection. Zandbergen[22] evaluated the GPS performance of 3G iPhone using three positioning technologies: A-GPS, WiFi positioning and cellular network positioning. The study found the accuracy of iPhone was inferior to regular GPS data loggers, with the average median error of 8 m using A-GPS method, 74 m using WiFi positioning method, and 600 m using the cellular positioning method. Michael et al[29] evaluated a customized GPS system in Motorola i760 under static and moving conditions in Portland, Oregon. The study reported a battery life of 18–19 hours and a spatial error of 11–15 m at outdoor static location for the GPS-enabled cell phone. Signal loss rate was found to vary by built environment (eg, highest at under-cover locations and lowest in open areas) and mode of transportation (eg, highest on public transportation, followed by walking, and then passenger car).

Discussion of Results from Our Study

Our study extends the insights of previous studies by testing multiple devices in challenging locations (eg, indoor, outdoor adjacent building structures, in-transit, and street canyon conditions). We found the median positional accuracy for all the tested devices to be approximately 10–21 m, 4–12 m, and 5–8 m for the static indoor, static outdoor, and outdoor moving conditions, respectively. The spatial errors were on the high side in this study compared to the previous studies because we deliberately tested more or less blocked environments (eg, indoor, outdoor adjacent to buildings, walking and driving in street canyon conditions). Our tested GPS devices performed better when driving in a car/bus than walking in downtown Los Angeles, in agreement with Michael et al study.[29] During static monitoring, spatial errors were lower outdoors (up to 6.1 m from a building structure) than indoor locations. These results can be explained partly by the HDOP values that revealed the satellite distributions and the blockage of satellite signals from adjacent buildings. However, our results showed that the indoor/outdoor distinction is an ongoing challenge for the GPS devices and air pollution epidemiological researchers. This problem is particularly important in areas packed with medium- to high-rise buildings and a dense population (eg, offices, commercial buildings, and apartments) because of the blockage of satellites by adjacent buildings and the multi-path problem. Further research is needed to assess whether systematic directional patterns in the GPS spatial error can be used to help differentiate indoor vs. outdoor locations with detailed information on the surrounding structures.

Our findings reiterate that across multiple devices, greater capability of capturing satellite signals does not mean higher positional accuracy. For instance, among all the tested devices BT-Q1000x had the lowest signal loss rate, indicating its strong capability to capture satellite signals; however, it sometimes output low-accuracy data under conditions with poor satellite signals (eg, indoors), resulting in location misclassification. On the other hand, complete loss of satellite signals indoors may not be a drawback because it can help determine whether people are indoors or outdoors. For instance, home indoors can be determined from long-term signal loss (GPS power on) after a subject enters a residential house. Under such conditions, no output from a GPS device is better than low spatial accuracy GPS outputs.

As expected, out tests revealed longer acquisition time occurs in a cold start than a warm start. During warm start, the GPS receiver remembers its last calculated position, almanac used, and the coordinated universal time. The receiver has a general idea of which satellites to look for because it knows its last position and the almanac helps identify which satellites are visible in the sky. While in cold start, the GPS receiver dumps all information and resets (no known information is available). It then attempts to locate satellites and lock a satellite signal from all of the satellites, which takes a lot longer. There is another condition named "hot start" when the GPS device restarts within 2 hours. The GPS receiver remembers all the information as in the warm start as well as which satellites were in view, thus it takes the least time to regain the a GPS lock. In this study we found little difference in acquisition time between warm starts and hot starts (results not shown). Stopher et al[11] found highly variable acquisition time, ranging from as little as 15 seconds to as much as 120 seconds under static conditions. We observed more variable acquisition time from 15 seconds to 15 minutes or more depending on the presence or absence of tall building structures and on whether the device was turned on and put in motion immediately after it was taken out of a building. In our experiments, all the GPS devices could fix locations within 10 minutes while moving except E71, which had the longest acquisition time or worst capability to capture satellite signals under all the conditions. For cold starts, the fastest acquisition time was observed in outdoor static tests because outdoor and static condition favors quick location fixing. Under warm start conditions, the acquisition time was similar between static outdoor and moving conditions.

We tested only two cell phones, one on an Android software platform (GPhone) and the other on a Symbian software platform (E71). We find remarkably higher signal loss rate in E71 than the data loggers but comparable or somewhat better spatial accuracy performance and often shorter acquisition time in GPhone than the data loggers likely because of the A-GPS in GPhone and the cell phone network. Two major limitations of the GPhone in this study are 1) short battery life (<8 hours when running GPS continuously while taking phones calls for approximately 10 minutes/day); and 2) unreliable GPS tracking program on the GPhone (losing GPS signals or automatically shutting down after 20 hours' continuous GPS operation). However, more recent models of GPhone and other GPS-enabled cell phones may have much longer battery life comparable to GPS data loggers.[29] In addition, newer versions of the software on the GPhone provides more data tracking and recording options and are likely more reliable. GPS cell phones have a potential advantage over the data loggers since they can be programmed to automatically upload location data through the cell phone network, which will enable researchers to monitor data quality more closely. In addition, they could send short message service messages to the subjects to notify of any problems or remind the subjects to perform certain activities (eg, filling out a diary). GPS-enabled cell phone technology and software capabilities are rapidly evolving and gaining wider market penetration and GPS cell phones will likely change the way we collect time-location data.

Although current advances in technologies make GPS devices feasible for monitoring people's daily activity patterns, barriers still exist for researchers to obtain accurate and comprehensive time-activity information, mainly under conditions with poor satellite signals such as skyscraper area or concrete buildings. Validated programs are needed that can automatically extract time-location information in different microenvironments, such as commuting, residential indoor, and workplace. Schuessler et al[32] demonstrated how to use GPS data to determine individual travel behavior, but future work is needed that can improve and implement these methods in the field of air pollution epidemiology, particularly with regards to distinguishing indoor and outdoor activity patterns.

Conclusions

All the tested GPS devices had limitations, but we identified several devices which showed promising performance for tracking subjects' time location patterns in epidemiological studies. The battery life of our tested instruments ranged from <9 hours to 48 hours. The acquisition of location time after startup ranged from 1 second to >30 minutes and varied significantly by building structure type and by cold or hot start. At fixed outdoor and indoor locations, 65%–95% and 50%–80% of GPS points fell within 20-m of the corresponding DOQQ locations for most of the devices. Under moving conditions, most of the GPS devices performed well on unobstructed freeways, but the performance was significantly impacted by surrounding structures on surface streets in highly urbanized areas. No single GPS device constantly outperformed the others among the seven GPS devices we tested, but the BT-Q1000x, BT-335, DG-100, and VGPS-900 data loggers are good candidates for daily monitoring of people's time-location patterns in air pollution health studies. The GPhone would also be an excellent choice given the improvement in the battery life, the reliability of recording programs, and the ability to support customized applications in the near future.

Authors' Contributions

JW is the PI of this study. JW conceptualized the study, participated in study design, oversaw the analysis, and drafted the manuscript. CJ conducted the field study and data analysis, and helped drafting the manuscript. ZL participated in the study design, field work, and data analysis in the early stage of the study. DH participated in the study design, reviewed the manuscript, and revised it critically for important intellectual content. GJ participated in the field work in the early stage of the study. RM helped conceptualize the study and provided important intellectual content for the manuscript. All authors assisted in the interpretation of results and contributed towards the final version of the manuscript.

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Abbreviations

A-GPS, assisted GPS; DOQQ, Digital Orthophoto Quarter Quadrangle; DOP, dilution of precision; GPS, portable global positioning system; HDOP, Horizontal dilution of precision; UCI, University of California, Irvine; USC, University of Southern California; USGS, US Geological Survey; WAAS, Wide Area Augmentation System.

Disclosure

This manuscript has been read and approved by all authors. This paper is unique and is not under consideration by any other publication and has not been published elsewhere. The authors and peer reviewers of this paper report no conflicts of interest. The authors confirm that they have permission to reproduce any copyrighted material.

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Supplementary Figure

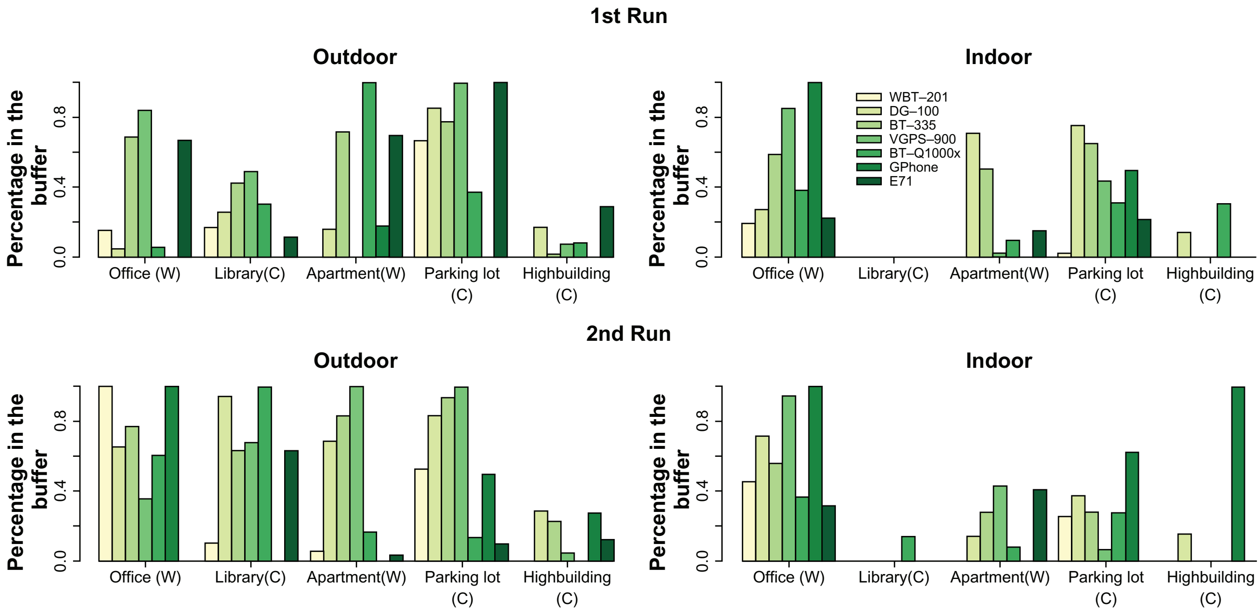

Figure S1. Percentage of recorded GPS data points in a 10-m buffer of individual sampling sites 3.0 m from the major door or window in the 17-minutes[a] static place tests (W: wood, C: concrete).
Note: [a]The first minute of GPS data was removed because unstable records may occur immediately after turning on or relocating the instruments from one location to another.